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REAL-TIME MEASUREMENTS OF EMISSIONS FROM AN AIRTIGHT WOODSTOVE

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ABSTRACT

A technique for real-time measurement of CO and NO_x emissions from woodstoves is described. Preliminary measurements indicate CO emission factors of 2 to 10
× 20 = g/kg
micrograms per Joule (μg/J) of heat release and NO_x emission factors of 0.01 to 0.09 μg/J when burning unseasoned hickory in an airtight stove.

INTRODUCTION

In the last ten years there has been a tremendous resurgence in the use of wood as a fuel for residential comfort heating. This increase is indicated by a current sales rate of around one million woodstoves per year (1), most of which are of the type commonly known as airtight stoves. This designation indicates a stove design which restricts air flow through the stove, requiring less cold air to infiltrate the dwelling and giving lower sensible energy losses out the flue. It is difficult to accurately quantify the contribution of wood energy to residential heating, but estimates place it in the range of 0.2 to 0.4 x 10^{18} Joules per year (1, 2). While it is recognized that wood will probably not regain status as the predominant means of home heating in this country, it is likely that wood use will continue to increase. This increase leads to concern that the emissions from these stoves could become an environmental hazard.

Unfortunately, few data are currently available on the emissions from residential woodstoves. Values of woodstove emission factors (emission factor ≡ μg pollutant/J heat release) for various pollutants are given in Table 1, along with data for home heating systems which burn fuel oil, natural gas, and

Table 1. Emission Factors for Residential Heaters.

All entries are in units of μg/J.

Heater Type	Ref.	Polycyclic Organic Matter	Condensable Organics	Particulate	Sulfur Oxides	Volatile Hydrocarbons	Carbon Monoxide	Nitrogen Oxides
Woodstove	3	0.02	0.4	0.2	0.006	0.1	10.	0.03
Woodstove	6		0.2 [a]					
Woodstove	4		0.5 [a]					
Distillate Oil Boiler[b]	7			0.008		0.003[c]	0.016	0.06
Natural Gas	7			0.004	0.0002	0.003[c]	0.01	0.03
Coal Boiler	8	0.01	0.05	0.1	0.5		0.02	0.1
Coal Furnace	8	0.001	0.1	0.4	0.5		0.4	0.2

[a] In this study, condensable organics and particulate were collected together and weighed. A heating value of 19 MJ/kg as received basis was assumed.

[b] Fuel heating value assumed to be 46 MJ/kg.

[c] As methane.

coal. The choice of μg/J as the units for these factors facilitates the comparison of emissions from fuels with significantly different heating values per unit mass. The tabulated values represent averages from each investigation, and it should be noted that large variations in these factors occur due to differences in combustion conditions which are not under the control of the experimenter. As examples, replicate tests by DeAngelis, et al. (3) give measured particulate emissions different by a factor of seven, while the Butcher and Sorenson (4) data indicate combined particulate/condensable organic emission factors different by a factor of six for near-replicate tests. Despite the variation of emissions due to combustion conditions, it is clear that woodstoves emit large amounts of pollutants both when compared to alternative heating systems and as a percentage of nationwide emissions. Assuming a CO emission factor of 7 μg/J (averages of reference 3 data indicate ca. 1.5 μg/J for fireplaces and 11 μg/J for woodstoves) and a current annual wood use of 0.3×10^{18} J, the national CO output from residential woodburning would be 1.5×10^{6} Mg/year, about 2% of the national total.

The present investigation represents the beginning of an effort to develop techniques which are suitable for evaluating the effects of variables such as fuel type, fuel preparation state, firing rate, secondary air regulation, and stove design on emissions and efficiency of woodstoves. Time-average techniques such as isokinetic sampling are ill-suited for such evaluation due to two reasons. First, the run-to-run variability of woodstove emissions (affected by such factors as initial arrangement of fuel and abrupt changes in fuel-bed geometry due to settling) would require many replicate tests to determine the effect of a single variable. Second, large measurement errors are likely for data based on isokinetic sampling of very low velocity (ca. 1 to 4 m/s) stack gases. Real-time measurements allow rapid quantification of effects of controlled variables, since the experimenter can vary air addition rates, baffle angles, etc. on a time scale which is short compared to the time scale for changes in the variables over which there is no control. A further advantage of real-time techniques is that the portions of a woodstove's burning cycle (start-up, refueling, burn-out) which contribute most to emissions or are associated with low efficiency may be readily identified for further research.

Of the emissions listed in Table 1, polycyclic organics probably represent the most serious environmental hazard. Due to the difficulty of making real-time POM measurements, our work is geared toward inference of POM emission rates by measurement of proxy compounds. DeAngelis' data (Figures 1 and 2) for fireplaces and airtight stoves suggest that combustion of wood gives low POM emissions when NO_x emissions are high and CO emissions are low, as might be expected from kinetic considerations. However, it is not certain that woodstove design modifications which produce low CO and/or high NO_x emissions will necessarily produce low POM emissions. The authors feel that proxies (including but not limited to CO, NO_x, total unburned hydrocarbons, total condensable organics, and particulate) should be used to guide development of second-generation airtight stoves. The improved designs could then be subjected to EPA Method 5 type tests to confirm whether POM emissions are significantly lower than for present woodstoves.

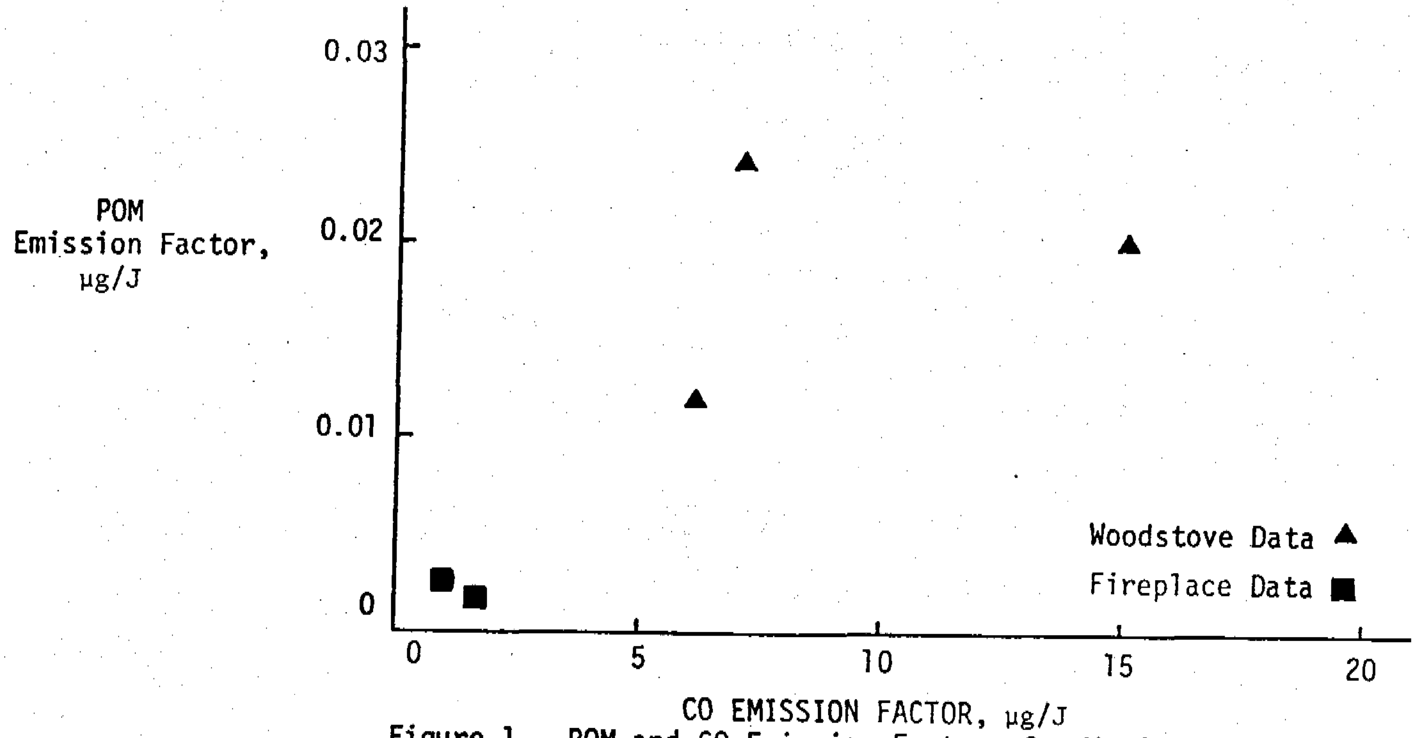

Figure 1. POM and CO Emission Factors for Wood Combustion. Data are from reference 3.

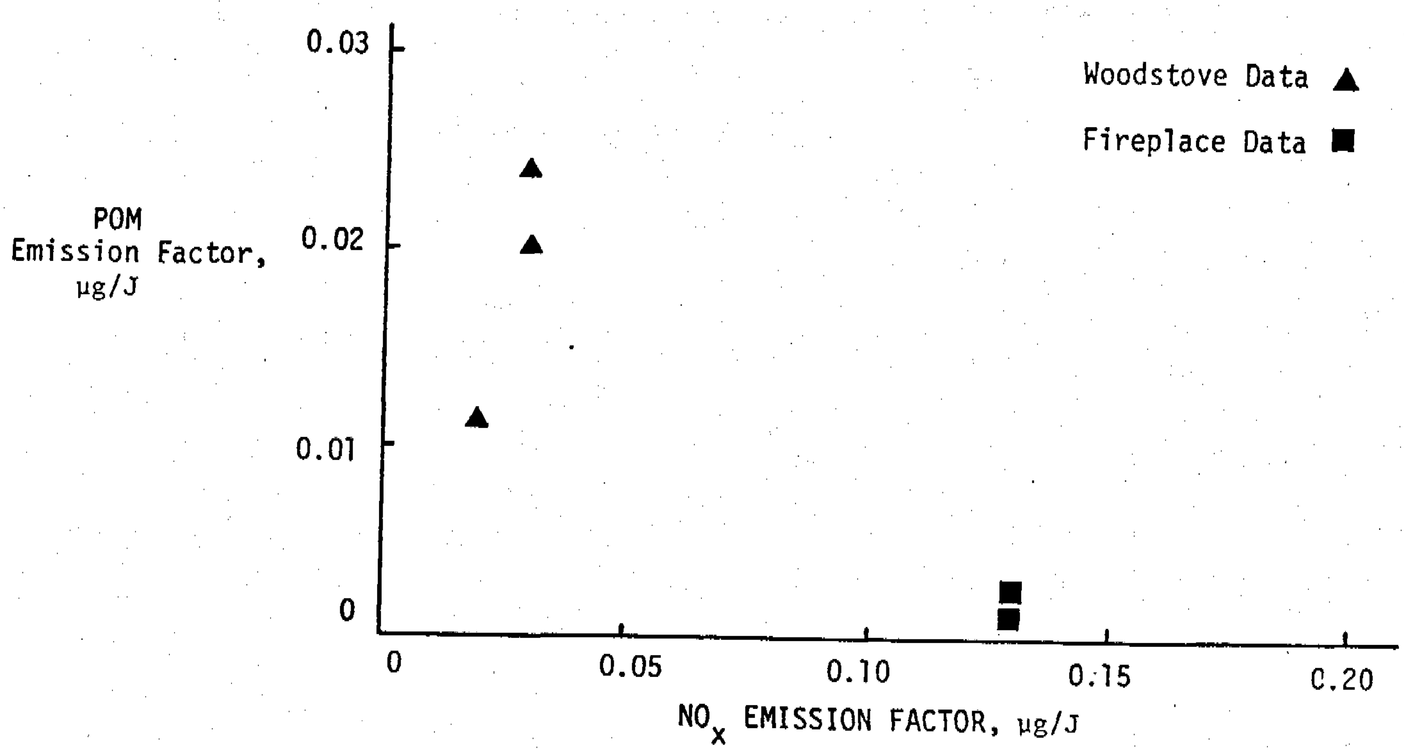

Figure 2. POM and NO$_x$ Emission Factors for Wood Combustion. Data are from reference 3.

EXPERIMENTAL APPARATUS

Woodstove

The woodstove used in this investigation is shown schematically in Fig. 3 and has primary and secondary air inlets. Primary air enters through a thermostatically controlled damper mounted on the door. The damper is preset by the manufacturer so that primary air flow will not be completely stopped, regardless of thermostat setting. The secondary air inlet consists of two 1.3 cm diameter holes located in the top half of the door. The holes can be partially or fully closed off by means of a manually adjustable plate. The stove has a false bottom with a grate in the center. Air which enters through the damper passes to the center of the stove and comes up through the grate, past the fuel. The secondary air inlets are intended to bleed air into the region above the charge, thereby providing oxygen for combustion of volatiles before they escape.

Stack Configuration and Instrumentation

The stove was used with the stack configuration and instrumentation shown in Fig. 4. Use of a blower to provide draft requires a barometric damper to ensure that the draft "seen" by the stove is not greater than would be experienced by a stove with an ordinary chimney. The stack diameter is 15 cm, and a 3.56 cm sharp-edge orifice is located 1.2 m downstream of the barometric damper. The orifice gives an easily measured pressure differential (ca. 7 cm H_2O), which, when combined with the measured gas temperature at the orifice, gives the flow rate past the sample probe. The stack is insulated downstream of the damper to help avoid condensation of organic species and to minimize errors in measurement of stack gas temperature.

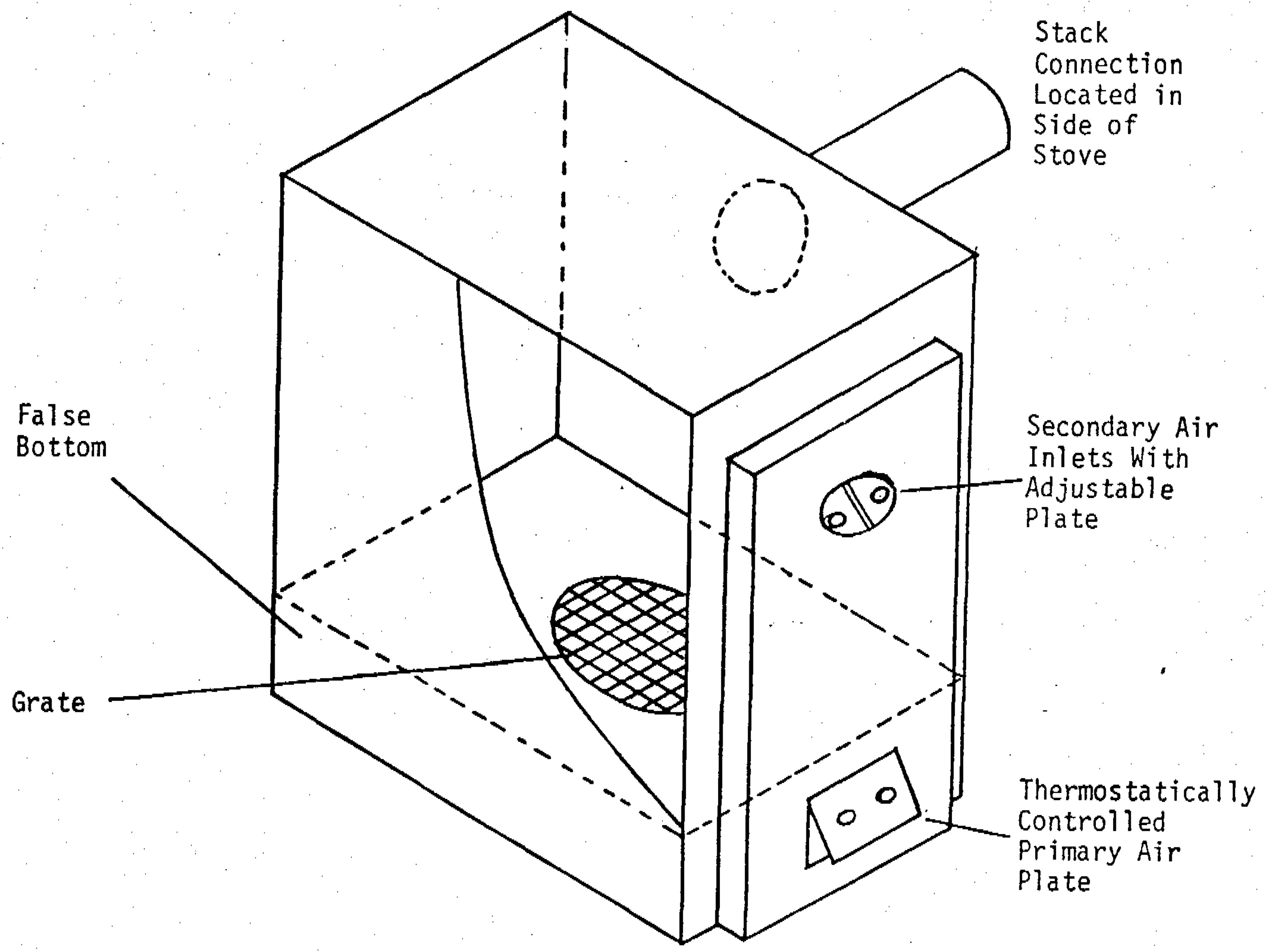

Fig. 3. Schematic Diagram of the Stove.

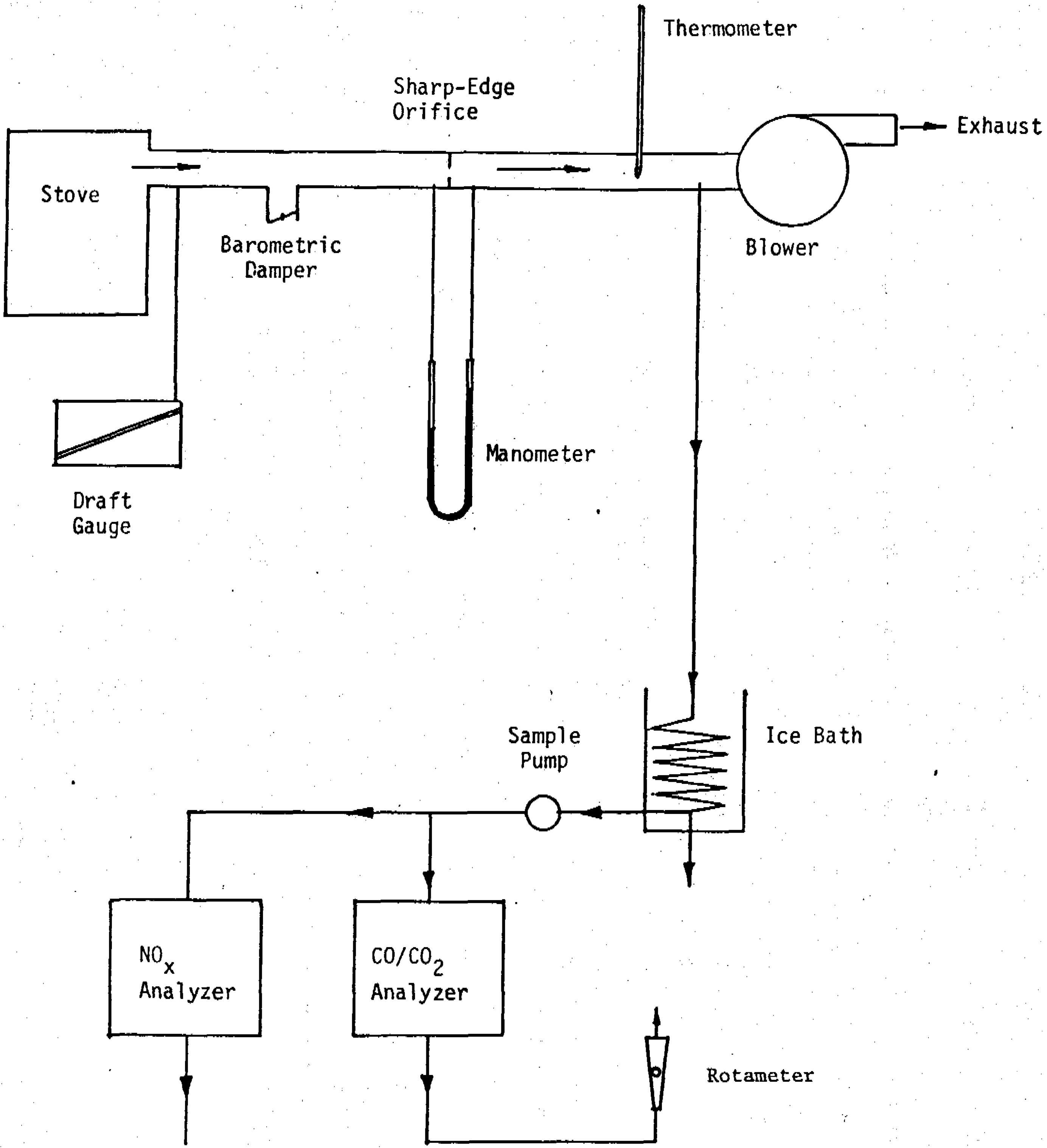

Fig. 4. Schematic of Woodstove Emission Measurement System.

EXPERIMENTAL PROCEDURE

To date we have conducted a limited number of runs. The procedure described here applies particularly to the run for which data are reported in this paper. To begin the run, crumpled paper was used to cover the floor of the fuel chamber. Kindling (1.5 kg), unsplit branches (3 to 10 cm diameter, 3 kg total mass), and larger pieces of hickory wood (some split, some unsplit, totaling 28 kg) were added to the chamber. This gave a total fuel charge of 32.5 kg, which approximately filled the stove. The blower was started and the barometric damper was adjusted to allow a draft of no greater than 2.5 mm H_2O. The strip-chart recorders were started, and the stove thermostat was set at its highest setting. The paper was lit with a match. The door was held open to allow observation of the fire (and a large flow of air through the stove) until it was judged that combustion would continue after shutting the door. A prior run had indicated the position of the secondary air control plate had little effect on the measured variables, and for this run the plate was in the closed position. Periodic adjustments were made to the stove and fuel during the run and are described in Figure 5. During the first 5 1/2 hours of the run, the pressure differential across the orifice, temperature of the gases downstream of the orifice, draft, and the reading of a mercury thermometer on top of the stove were recorded at intervals ranging from 3 to 47 minutes. A thermocouple and strip-chart recorder were used to monitor the stove temperature during the final 15 hours of the run. No orifice pressure differentials, gas temperatures, or draft readings were obtained during this portion of the run. However, the data indicated that interpolation between the values at 5 1/2 hours and the end of the run would be a reasonable procedure.

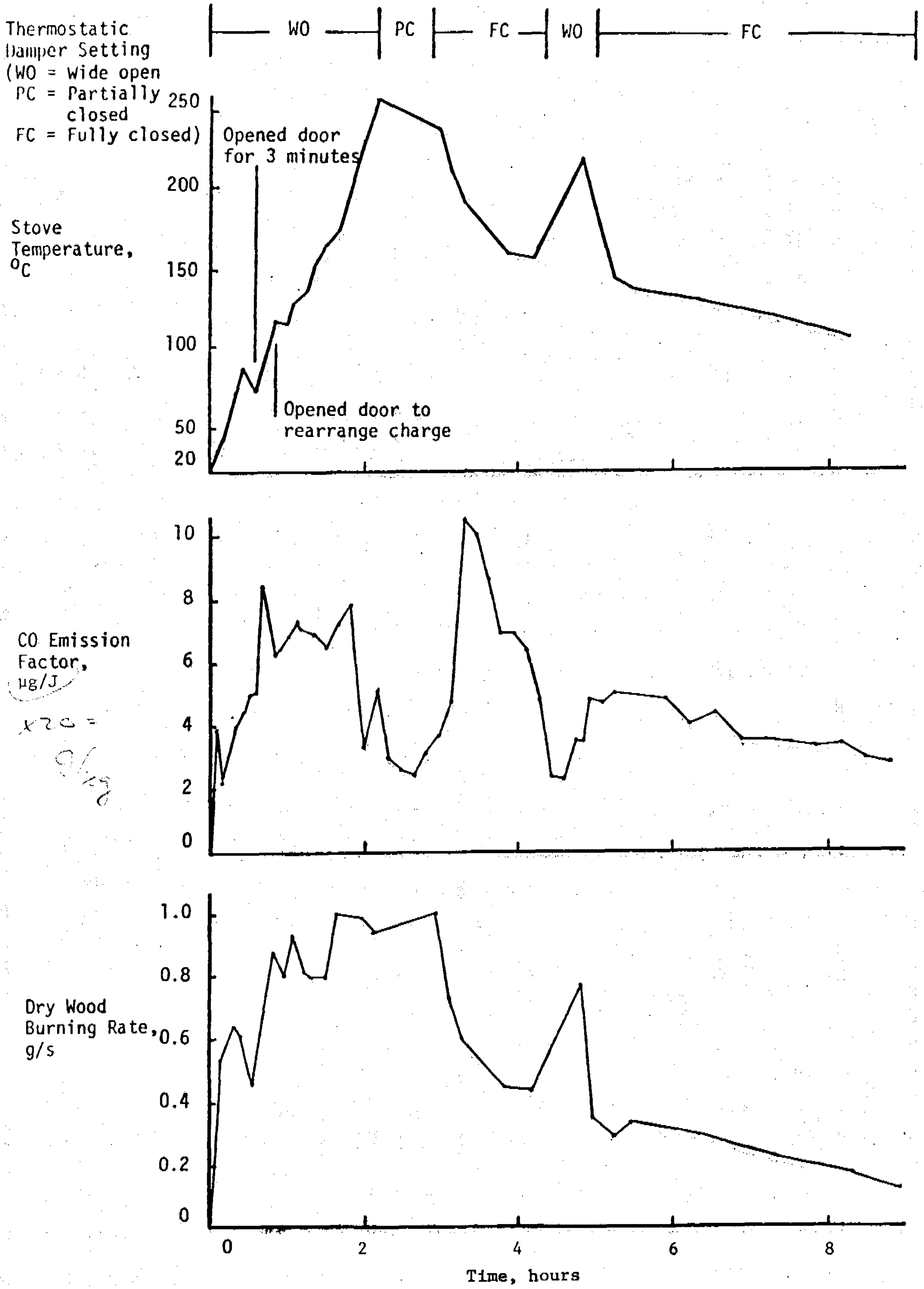

Figure 5. Real-Time Woodstove Performance.

Sample gases were continuously withdrawn from a location just downstream of the orifice. The gases were pulled through a trap maintained at 0°C to condense water and hydrocarbons before they reached the gas analyzers. It was necessary to install a pre-filter between the trap and the sample pump to protect the pump from particulate. A combination CO/CO_2 analyzer (Infrared Industries, model IR-702D) and a chemiluminescent NO_x analyzer (Bendix Corp., model 8102B, carbon convertor at 485°C) were used to obtain the CO, CO_2 and NO_x concentrations of the sample gases (dry basis). Concentrations were monitored using strip-chart recorders. Filter loading was inferred by rotameter measurement of the sample flow through the CO/CO_2 analyzer, and the filter was renewed whenever the flow dropped below the desired level.

RESULTS AND DISCUSSION

The stove temperature, instantaneous CO emission factor, and burning rate of the fuel are shown in Fig. 5 as functions of time after ignition. Slope discontinuities are a result of selecting a finite number of times for plotting purposes. The emission factors for CO and NO_x and the burning rate of the wood were calculated using the assumptions and procedures described in the Appendix. A trapezoidal integration of the burning rate data (for the entire burn, using estimates of orifice ΔP and T during the overnight portion of the burn) gave an estimated fuel consumption of 19.2 kg of dry wood during the burn. This figure may be compared to the initial charge of 32.5 kg as received wood, which is equivalent to 23 kg of dry wood if a moisture content of 30% (as received basis) is assumed. Equipment for moisture content determination was unavailable at the time of this test, but the history of the wood indicated a moisture content of 30% was a reasonable assumption.

The emission factors for CO (shown in Fig. 5) and NO_x (ranging from 0.02 to 0.1 μg/J compare favorably with the values reported by DeAngelis (3). The emission factor depends only on relative concentrations of CO, CO_2, and NO_x and is unaffected by any errors in measuring the flow rate through the stack. An anomaly regarding NO_x measurement was noted during the run. When the prefilter became clogged and the sample flow dropped to very low values, the NO_x reading increased by up to 100%. This behavior is as yet unexplained but may be due to NO-particulate interactions, which have been noted by Jaasma and Borman (7).

Figure 5 shows clearly the effects of thermostatic damper setting on burning rate and CO emission factor. The variation of CO emission factor with time indicates that use of periodic grab-bag samples to measure CO emissions is a questionable procedure.

In summary, a technique for real-time measurements of woodstove emissions has been developed. The technique has been used for measurement of CO and NO_x emissions, and it can be used for measurement of other species (such as total unburned hydrocarbons) for which continuous gas-analysis equipment is available. The use of forced draft and a sharp-edge orifice gives accurate measurement of stack-gas flow rate compared to pitot tube techniques. The flow rate measured using the orifice could also be used to determine the appropriate (isokinetic) flow rate for a particulate probe located upstream of the orifice. The authors view these measurement techniques as potentially powerful tools for the development of clean-burning residential woodstoves.

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APPENDIX

Computation of Emission Factors

The emission factor for a pollutant is customarily defined as the mass of pollutant per mass of as-received fuel burned. Numbers computed with this definition can be misleading when a fuel such as wood is considered, since the water content of the wood can account for up to 50% of the as-received mass. Also, the different heating values per unit mass of coal, oil, and wood tend to make comparisons between fuels more difficult. For these reasons, it was decided to express the emission indices in units of micrograms of pollutant per Joule of heat release. The emission factor in these units is given by the equation

$$EF_p = \frac{\dot{m}_p}{\dot{m}_B \ HHV} \tag{1}$$

where

EF_p = emission factor of the pollutant

$\dot{m}_p$ = mass flow rate of pollutant through the stack

$\dot{m}_B$ = mass burning rate of dry wood

HHV = higher heating value of dry wood (20 MJ/kg for hickory)

It is to be noted that $\dot{m}_B$ can not be estimated by placing the stove on a scale, unless the assumption is made that the rate at which absorbed water leaves the wood is at all times proportional to the rate at which the wood itself is being consumed.

Under the assumption that all the carbon in the fuel passes through the stack as CO or CO_2*, equation 1 can be rewritten as

$$EF_p = \frac{[p]\ \dot{n}\ M_p\ mf_c}{([CO] + [CO_2])\ \dot{n}\ M_c\ HHV} \tag{2}$$

where

[p] = mole fraction of the pollutant in the stack gas

[CO] = mole fraction of CO in the stack gas

$[CO_2]$ = mole fraction of CO_2 in the stack gas

$\dot{n}$ = gas-phase molar flow rate through the stack

M_p = molecular weight of the pollutant (28 for CO, 46 for NO_x)

M_c = molecular weight of carbon

mf_c = mass fraction of carbon in the dry wood (This number ranges from 0.50 - 0.56 for different wood species. For hickory, $mf_c = 0.50$)

Since the molar flow rate through the stack appears in both the numerator and denominator of the right hand side of equation 2, its value need not be known to compute the instantaneous emission factor.

Computation of Burning Rates

An estimate of the burning rate of dry wood was obtained by assuming that hydrogen, carbon, and oxygen were released by the wood in constant proportions

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*The data of reference 3 support this view. If carbon in the ash is assumed negligible, the carbon in the wood must leave as particulate, condensable organics, volatile hydrocarbons, CO, or CO_2. The sum of the emission factors for particulate, condensable organics, and volatile hydrocarbons indicates that they could account for at most 2% of the total carbon.

during the burn and that all the carbon passed through the stack as CO or CO_2. The first assumption must break down near the end of a burn when only coals are left, and further tests are planned to determine its validity during other parts of the burn cycle. The burning rate is then given by

$$\dot{m}_B = \frac{([CO] + [CO_2])\,\dot{n}\,M_c}{mf_c} \qquad (3)$$

The value of $\dot{n}$ was determined from the orifice data assuming a discharge coefficient of 0.60, ideal gas behavior, and 29 as the average molecular weight of the stack gases.